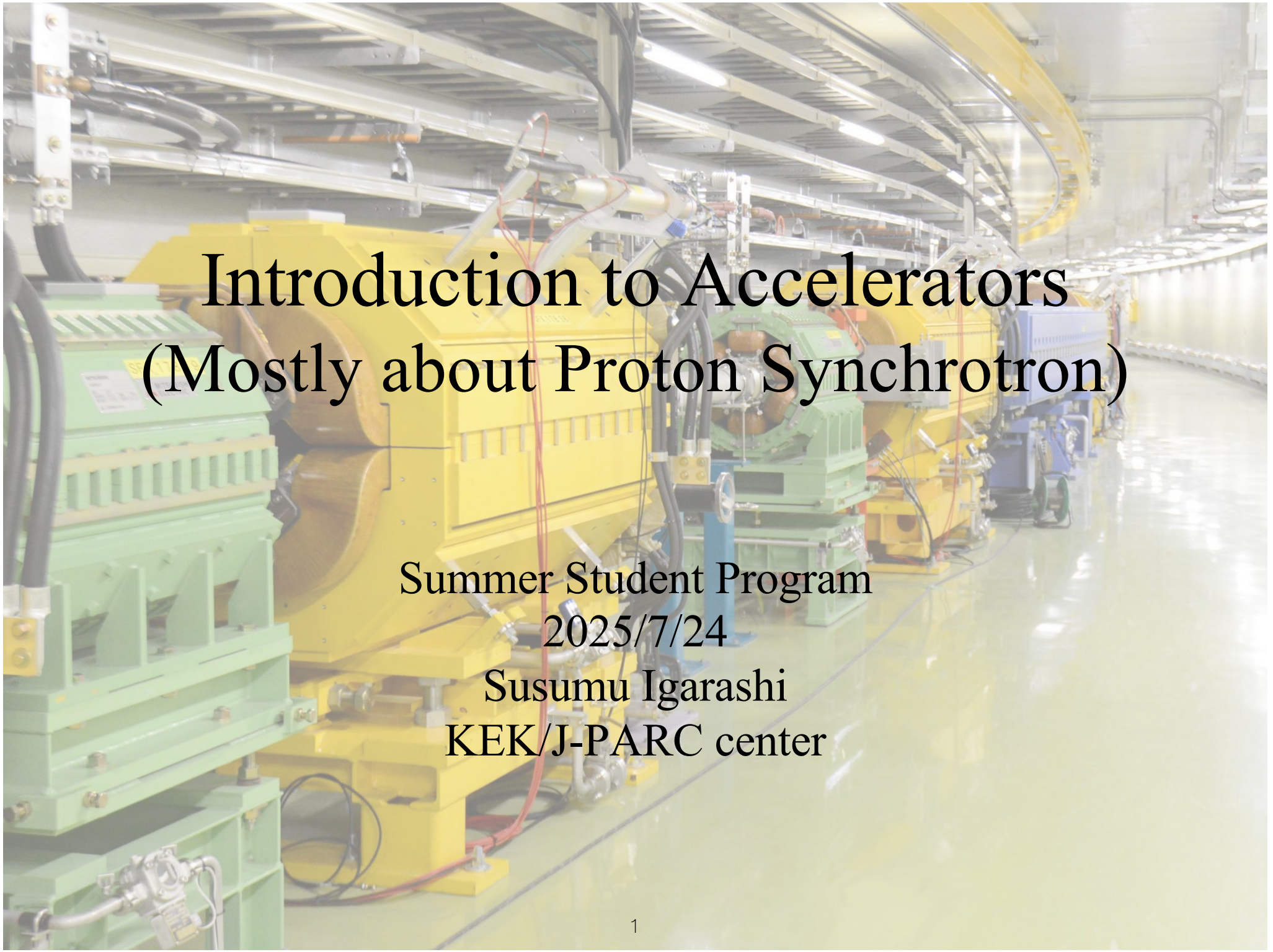


Introduction to Accelerators (Mostly about Proton Synchrotron)

Summer Student Program
2025/7/24

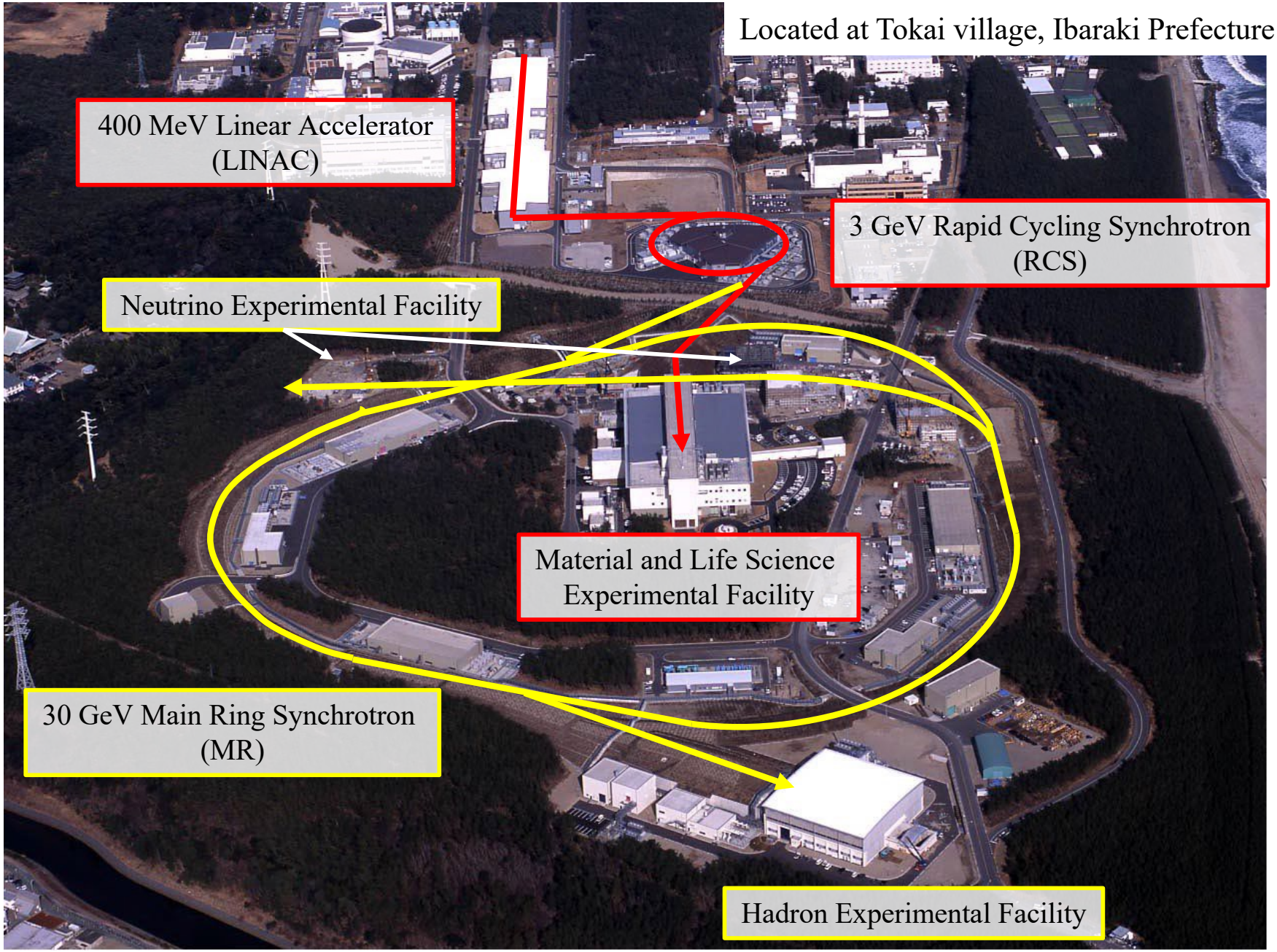
Susumu Igarashi
KEK/J-PARC center

Contents

- Introduction
- Synchrotron
- Efforts for performance improvement
- Accelerators in KEK
- Summary

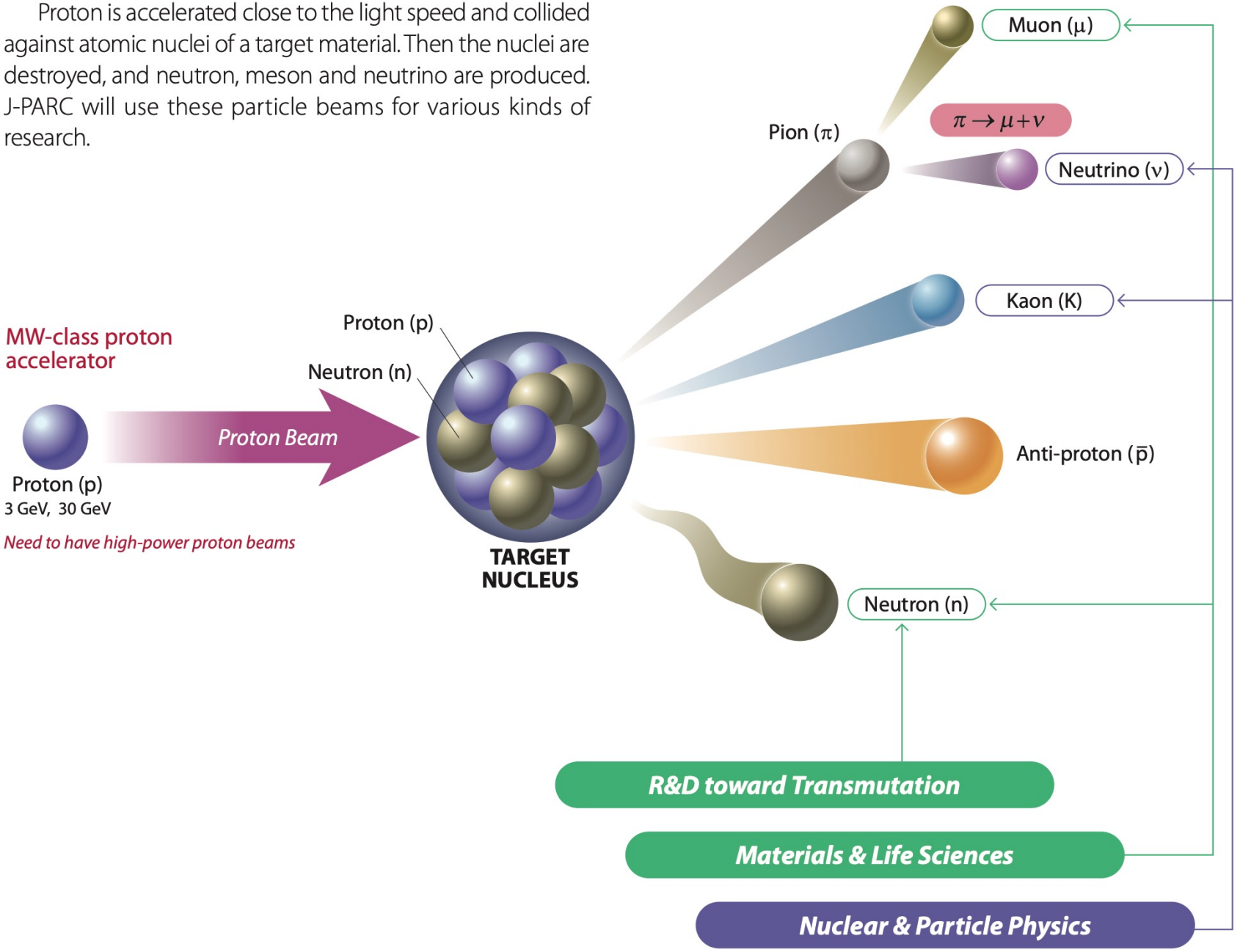
Japan Proton Accelerator Research Complex (J-PARC)

Located at Tokai village, Ibaraki Prefecture



Secondary beams produced with high-intensity proton beam

Proton is accelerated close to the light speed and collided against atomic nuclei of a target material. Then the nuclei are destroyed, and neutron, meson and neutrino are produced. J-PARC will use these particle beams for various kinds of research.



Contents

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- Synchrotron
- Efforts for performance improvement
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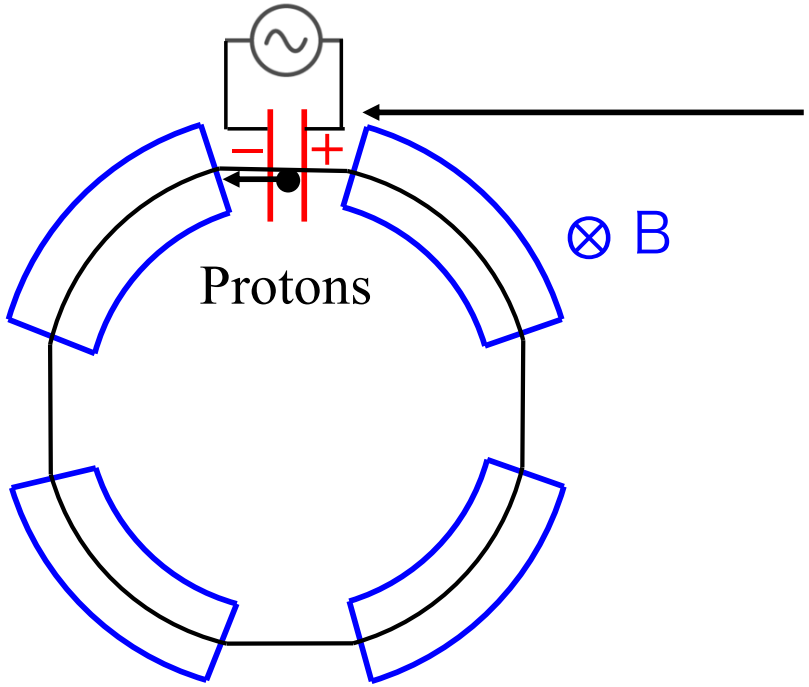
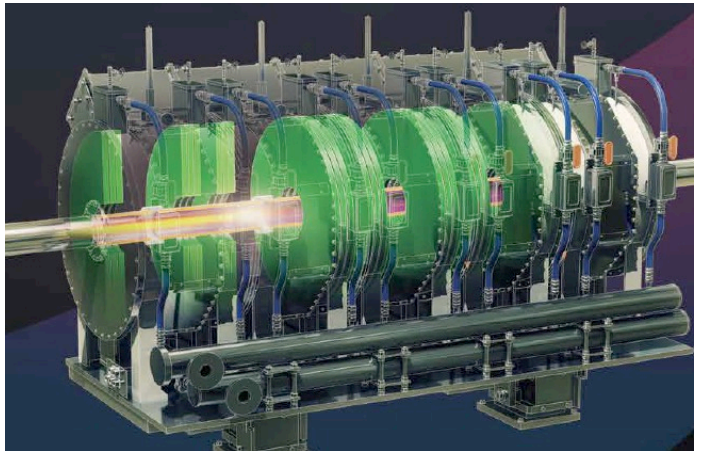
Synchrotron

- Circular Accelerator
- Magnets are to make a circular orbit.
- Radio Frequency (RF) accelerating cavities are to accelerate the charged particles (protons).
- Magnetic field strength of the magnets and frequency of the RF cavities should be synchronized.



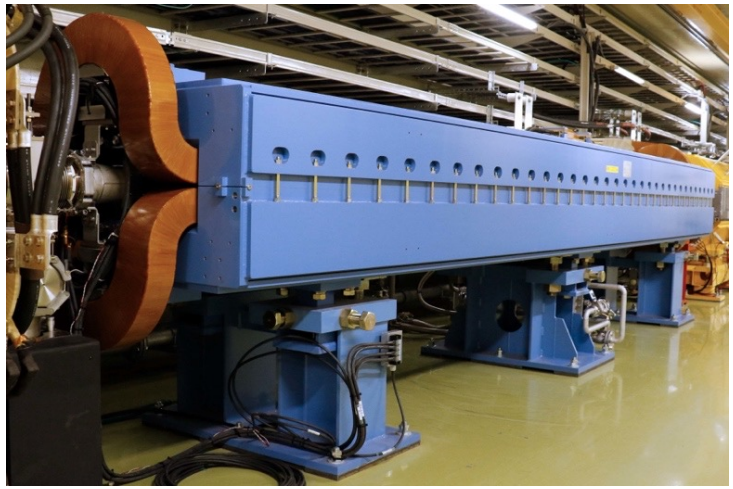
RF cavity



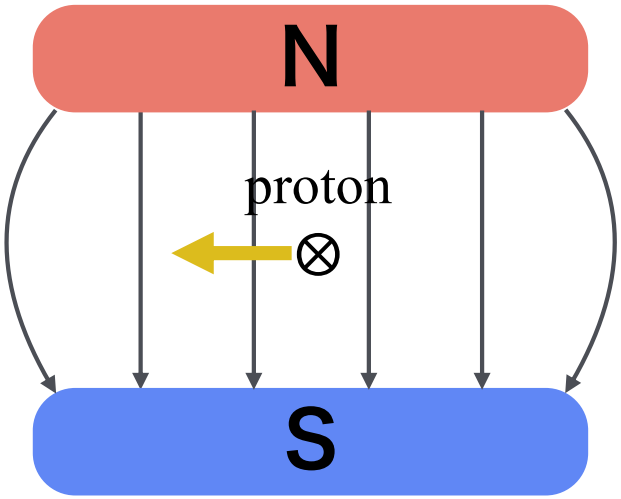
Protons are circulated about 100,000 turns and accelerated to the design energy.

Magnets to make a circular orbit

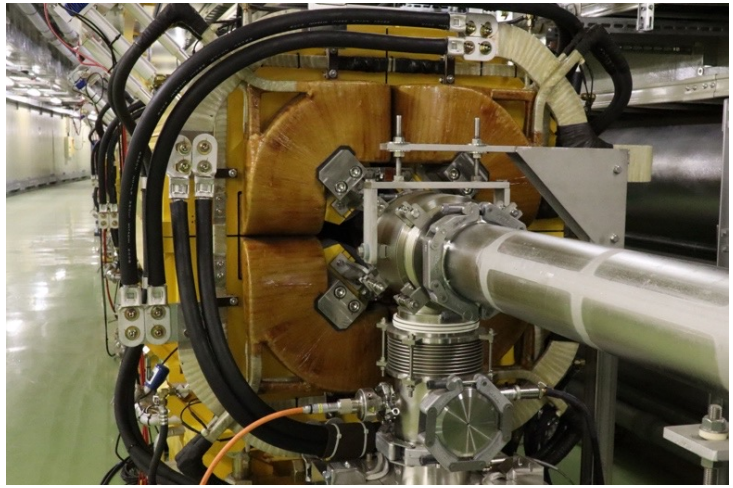
- Dipole magnets to bend beam

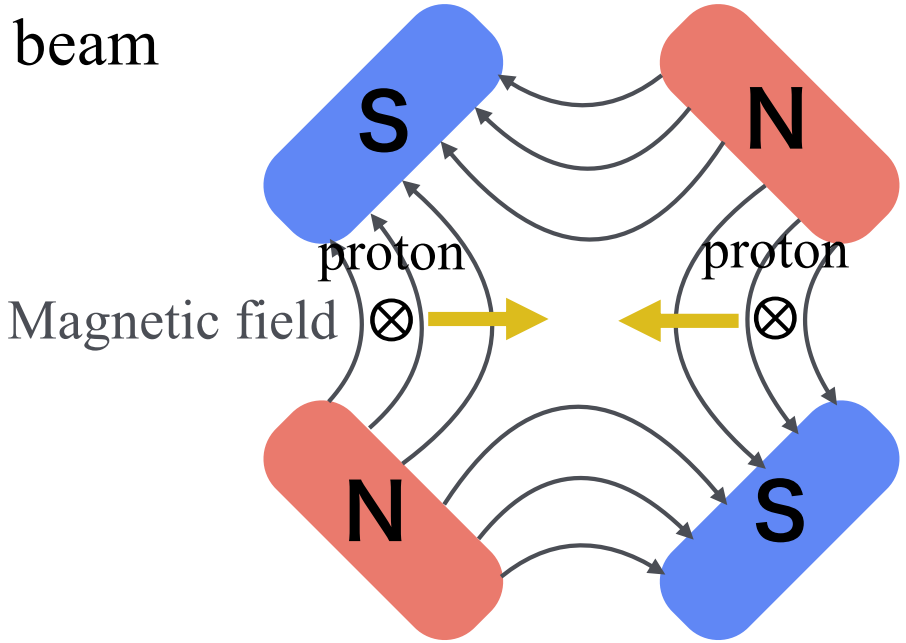


Magnetic field
0.12 ~ 1 Tesla
3 ~ 30 GeV



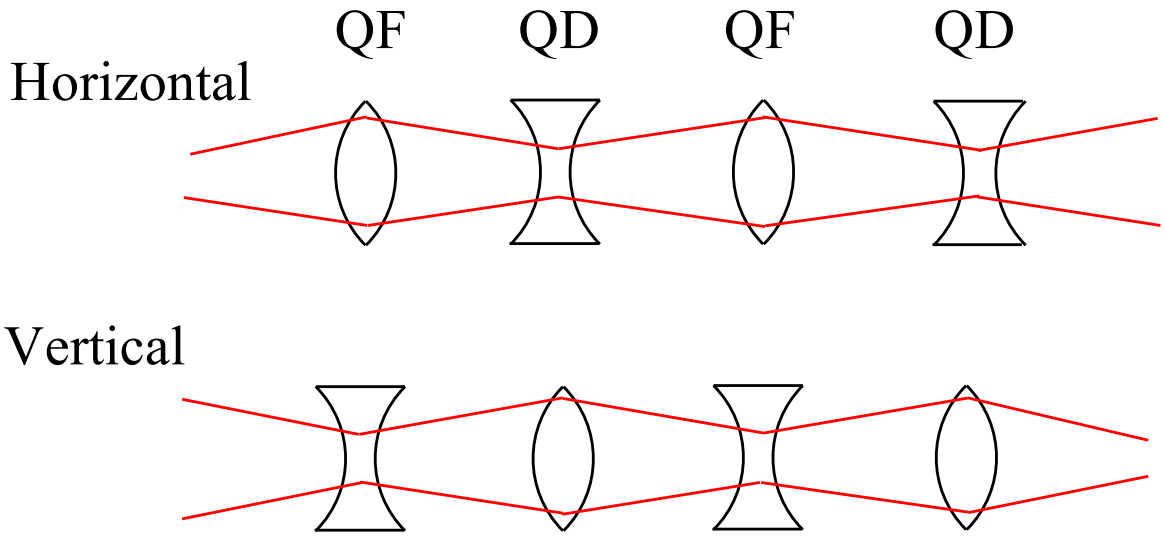
- Quadrupole magnets to focus beam

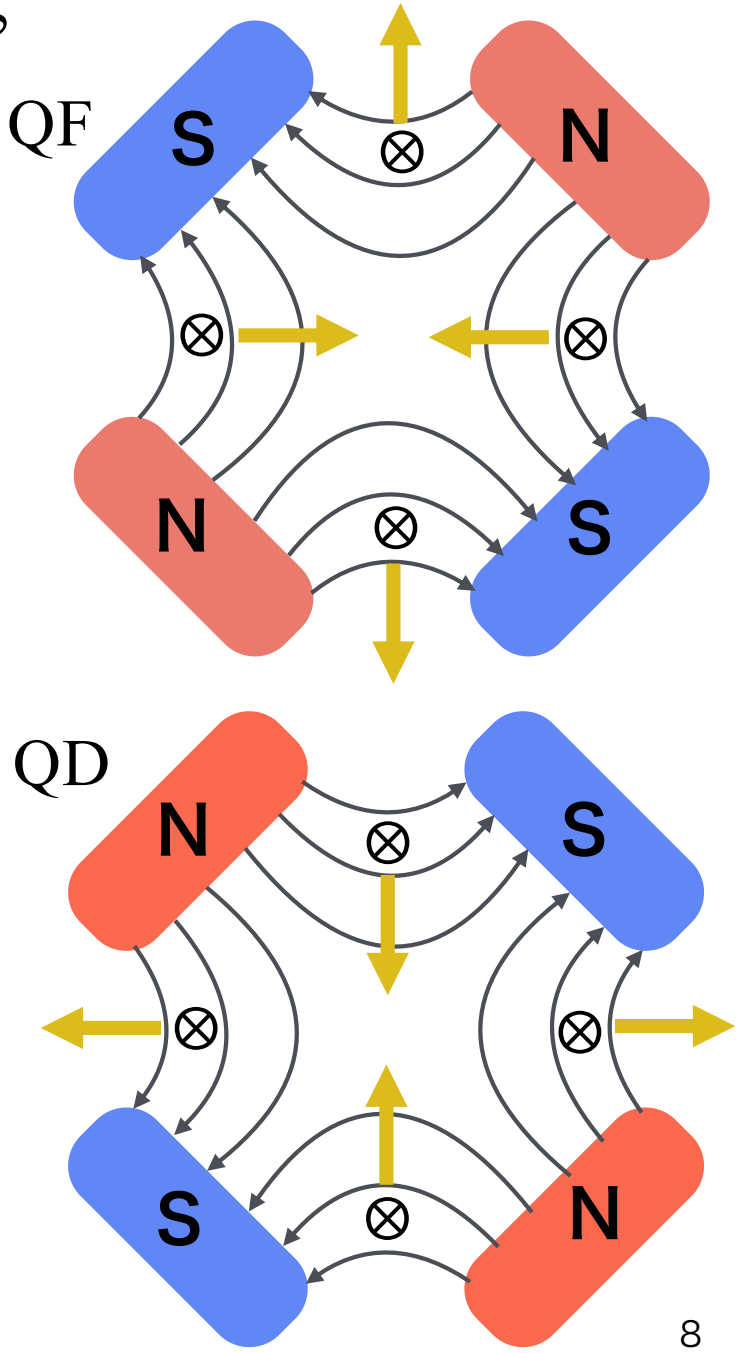




Beam Focusing

- Quadrupole Magnets
- QF (focus) : focus for horizontal and defocus for vertical
- QD (defocus) : defocus for horizontal and focus for vertical
- Beam passes through QF and QD alternately.
- Stability condition of betatron motion

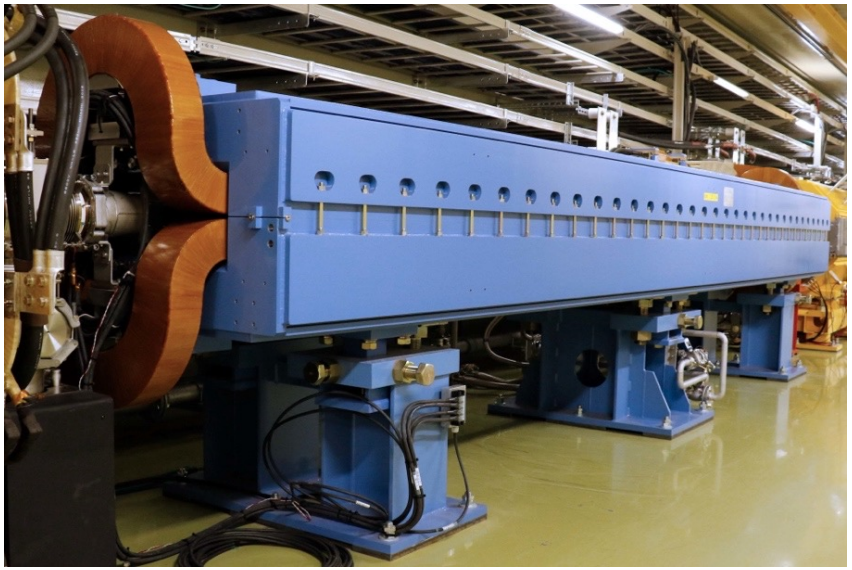




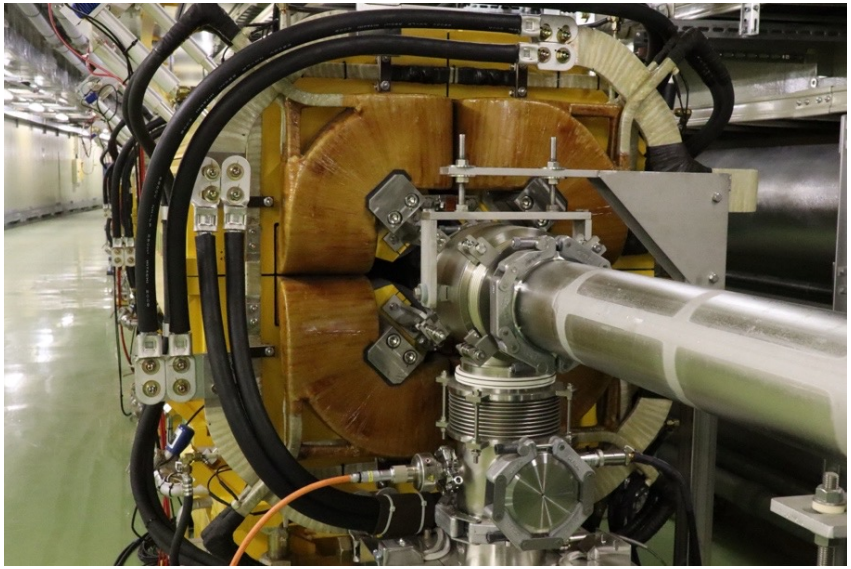
Requirement for the Magnetic Fields

- Proton should be stably circulated about 100,000 turns, which is about 100,000 km.
- Magnetic field must be accurate.
- Variation of bending magnets：$< 1\times10^{-3}$
- Uniformity of the magnetic field：about 5×10^{-4}
- Large aperture for high-intensity beam：10 cm ～ 15 cm

96 Bending Magnets

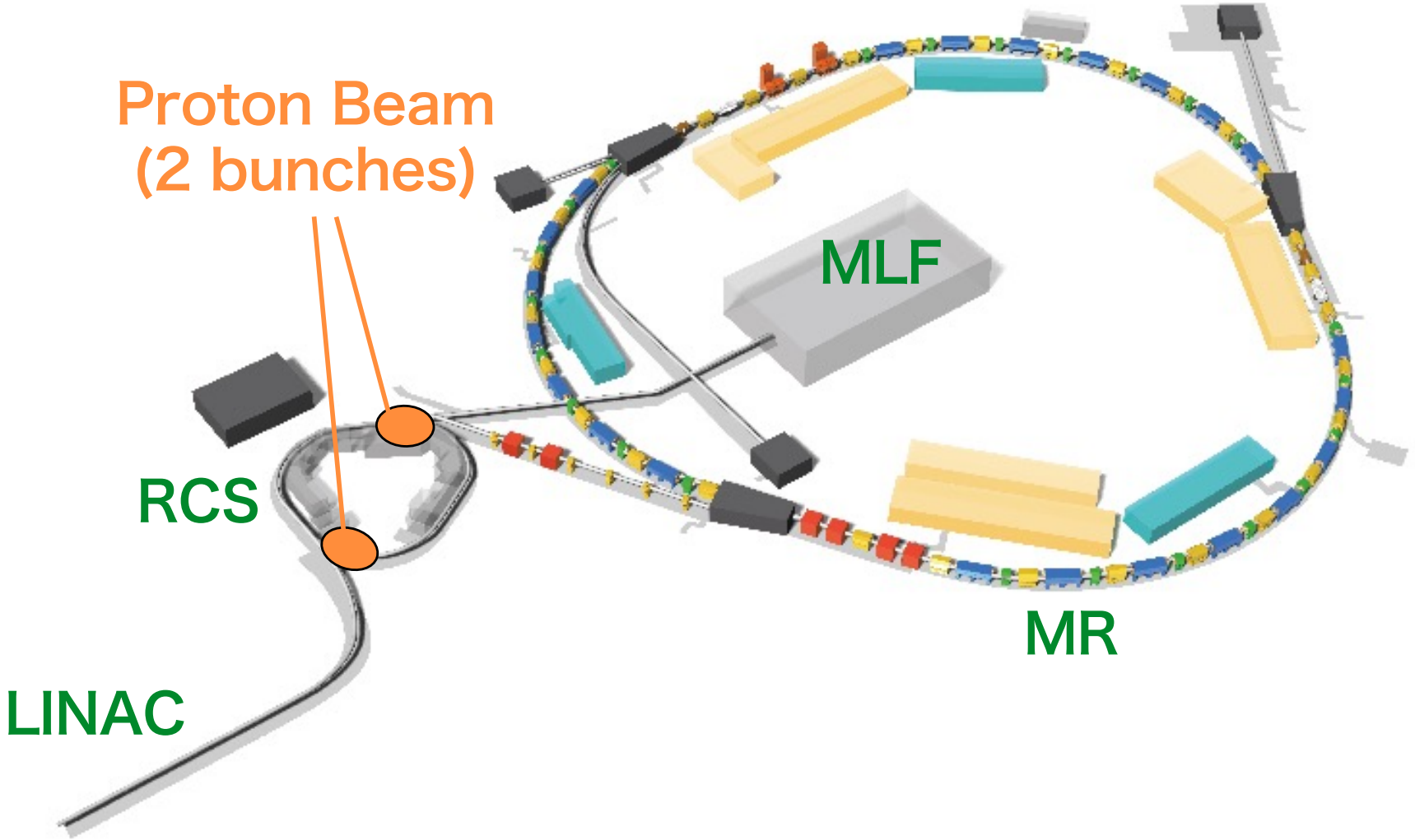


216 Quadrupole Magnets



Main Ring : Synchrotron Type

- Injection 3 GeV
- Acceleration 3 GeV → 30 GeV
- Extraction 30 GeV
- Recovery 30 GeV → 3 GeV



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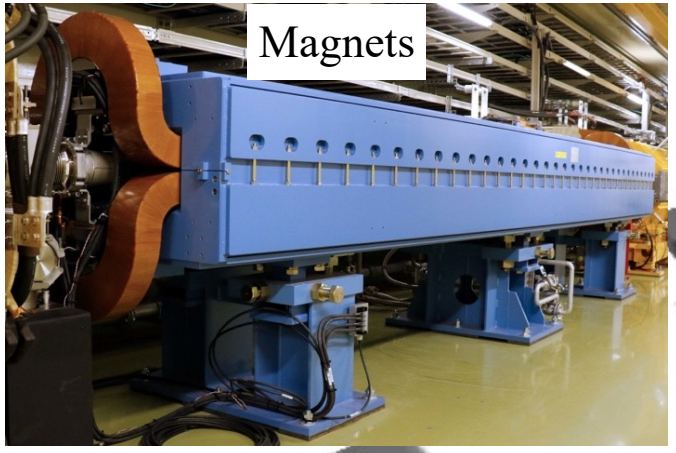

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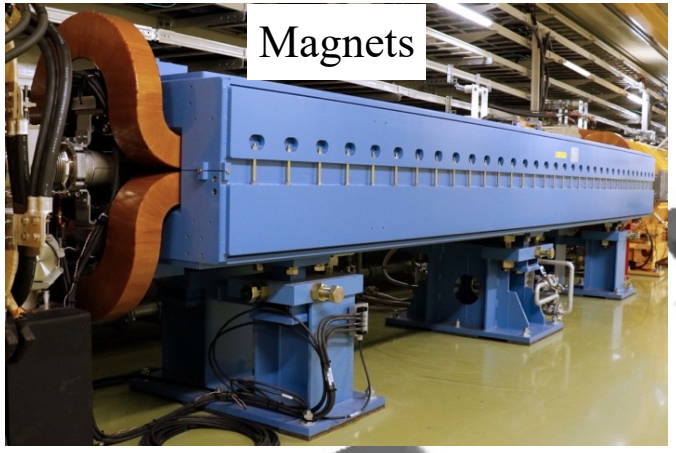

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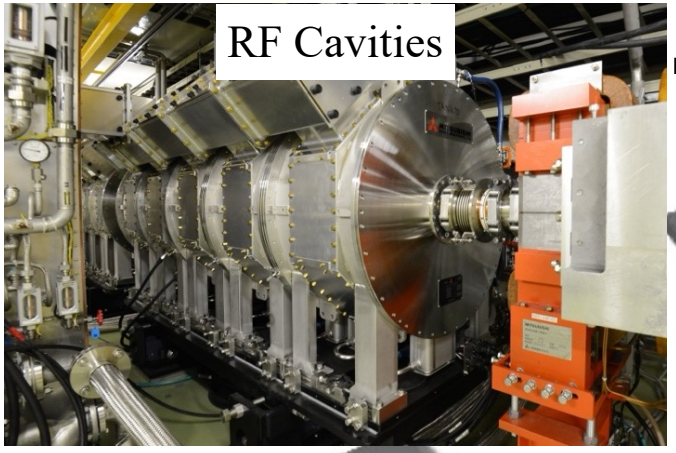
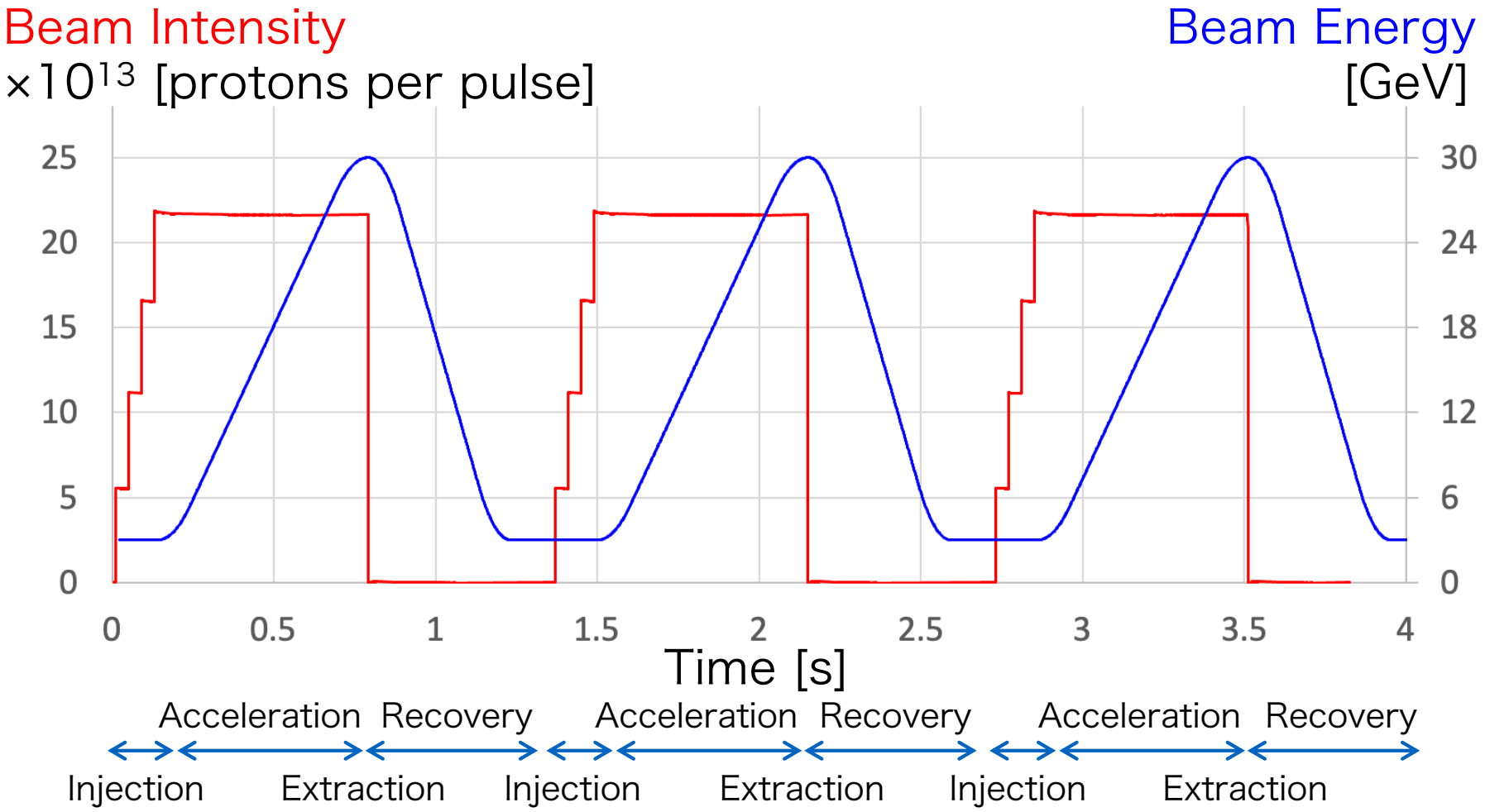


Main Ring : Synchrotron Type

- Injection 3 GeV
- Acceleration 3 GeV → 30 GeV
- Extraction 30 GeV
- Recovery 30 GeV → 3 GeV

Fast Extraction (FX) Beam Operation



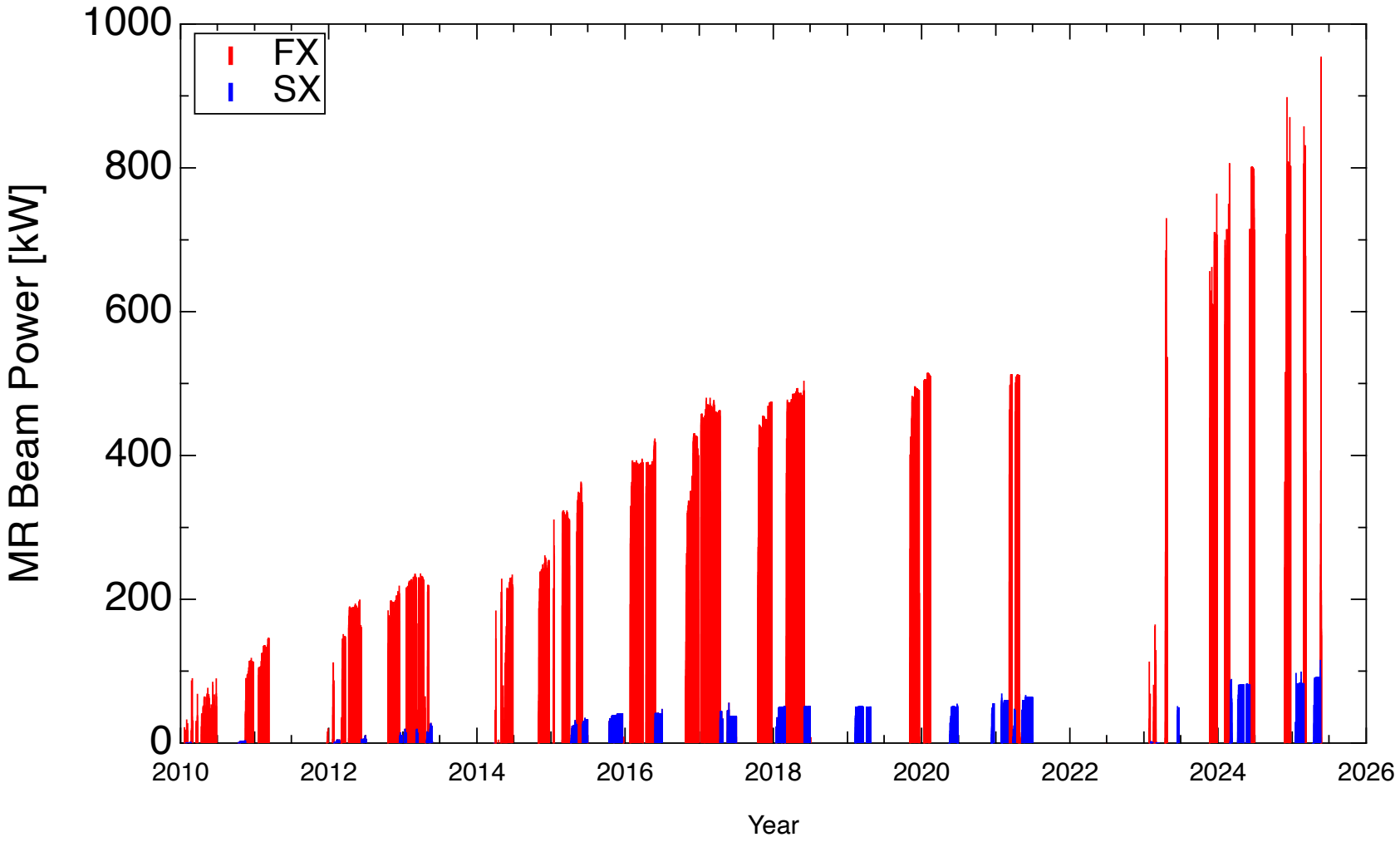
- J-PARC MR has the world record of 2.7×10^{14} protons per pulse (ppp) for the beam intensity of synchrotrons.
- We plan to increase the intensity to 3.3×10^{14} ppp.

Contents

- Introduction
- Synchrotron
- Efforts for performance improvement
- Accelerators in KEK
- Summary

MR Beam Power History

- Since the success or failure of an experiment depends greatly on the number of protons supplied, we have been enhancing the “beam power”, which is an indicator.
- Beam power = proton kinetic energy × number of protons extracted per unit time

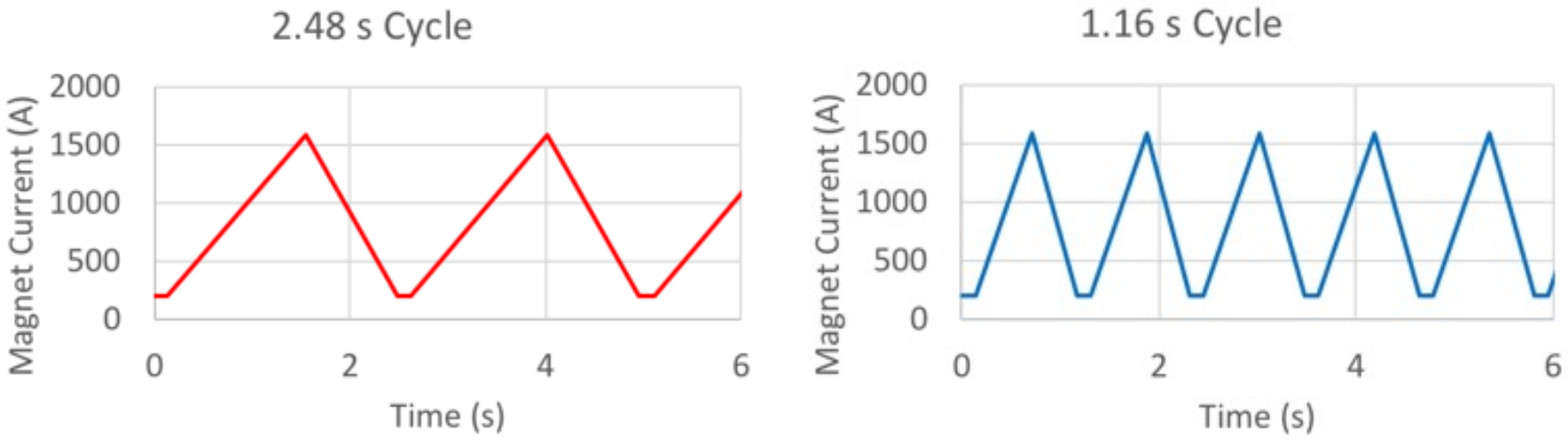


Beam Power

Beam power = proton kinetic energy × number of protons extracted per unit time

We are increasing the beam power with the following efforts.

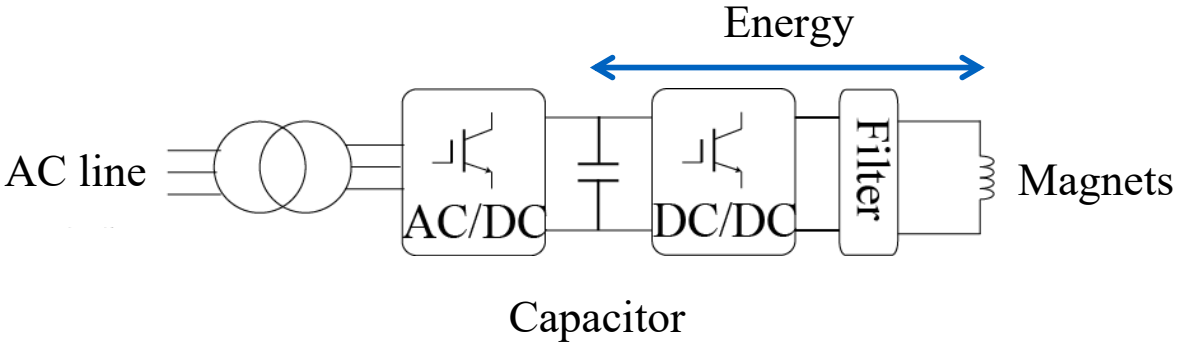
- Faster cycling to extract beam more frequently
- Increase the number of accelerated protons

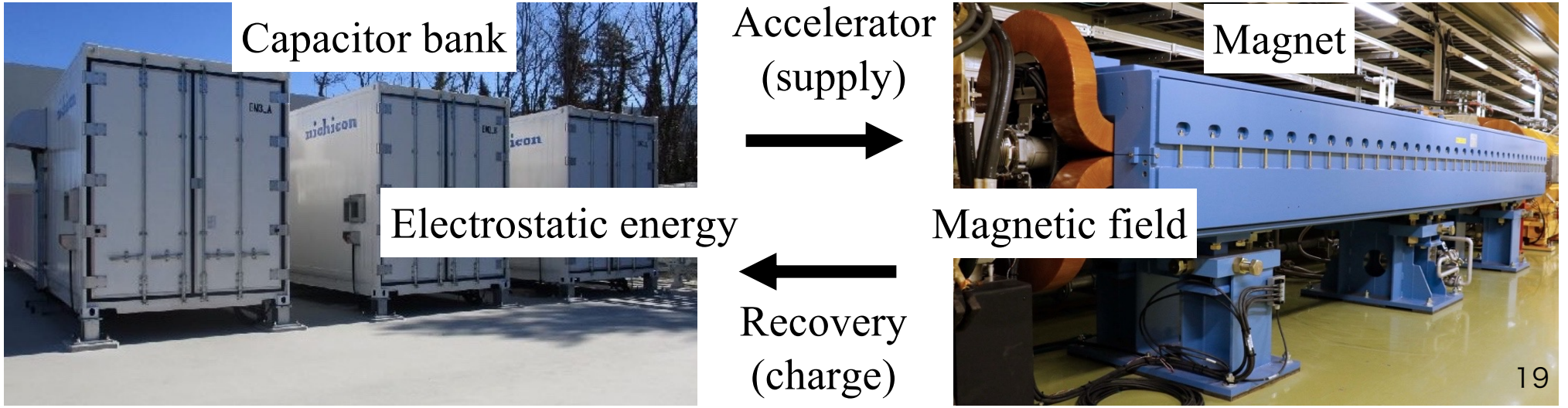


Magnet power supply upgrade for faster cycling

- New power supplies were constructed to supply the current to the magnets.
- Large capacitors are equipped for the energy storage.
- The stored energy in the magnets is efficiently reused.

Power supply for bending magnets

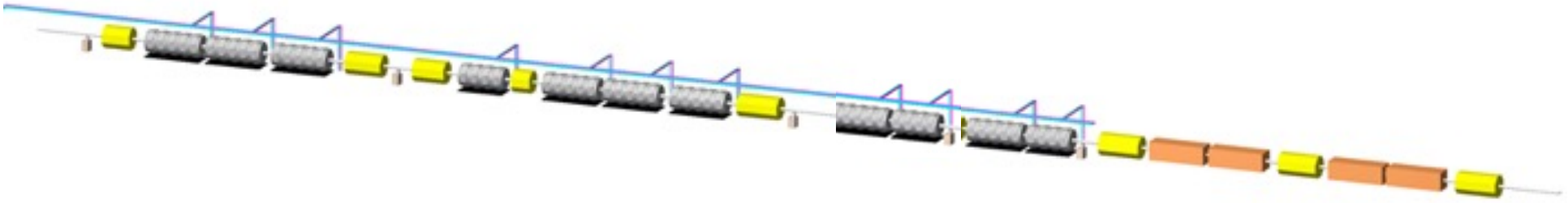




RF cavity upgrade for faster cycling

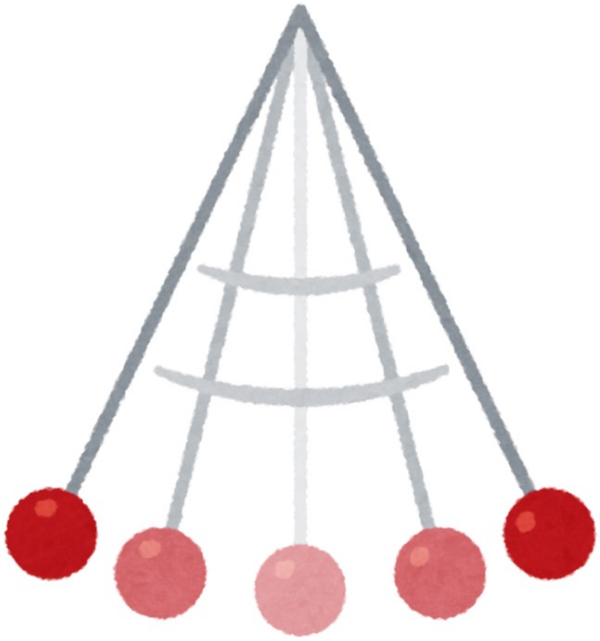
- Accelerating voltage should be higher for faster acceleration.
- We are increasing the number of RF cavities.

RF cavities being installed

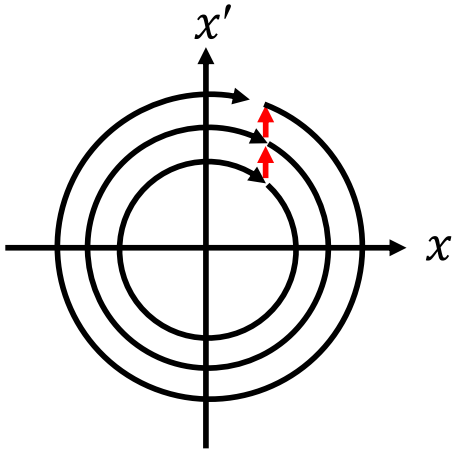


Beam Tuning

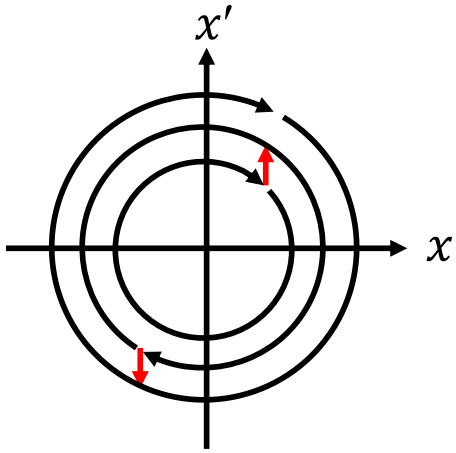
- Efforts to increase the number of accelerated protons
  - Beam is diffused with the following mechanisms.
    - Resonances of the betatron oscillations
    - Space charge effect
  - These effects are to be suppressed to increase the number of protons.



Integer resonance
ν_x = integer
Errors of the dipole magnets

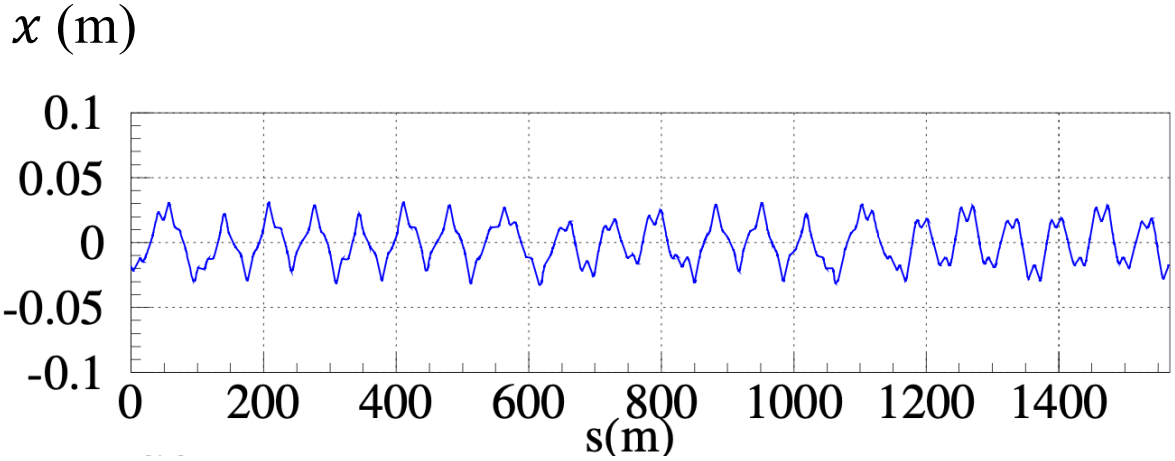


Half-integer resonance
$2\nu_x$ = integer
Errors of the quadrupole magnets

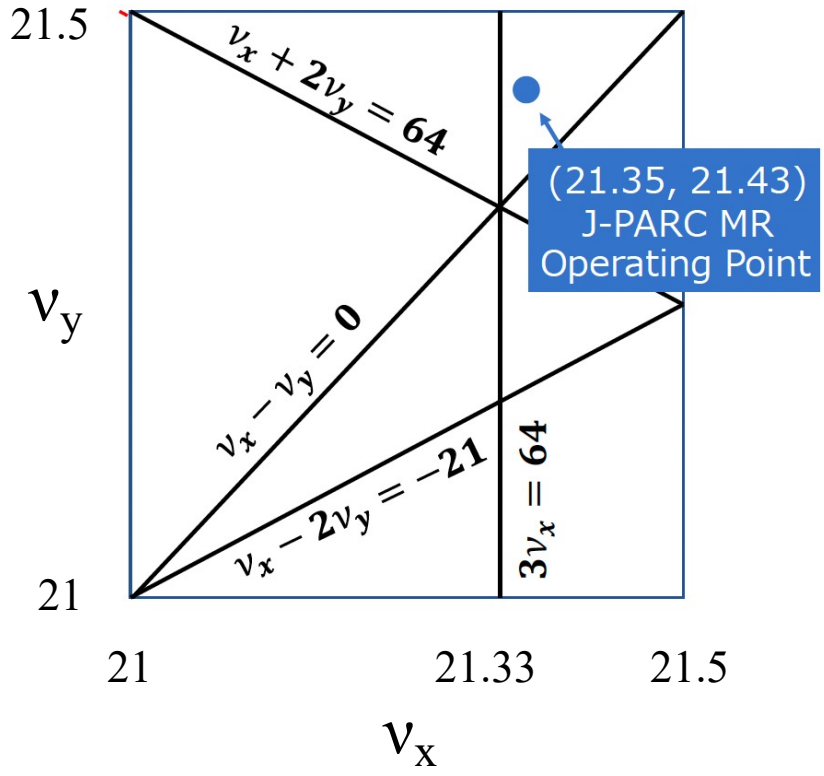


Resonances of the betatron oscillation

- Set the tune appropriately and avoid the resonances.
  - Tune : Number of betatron oscillation in a ring
  - Resonance : Amplitude of the betatron oscillation becomes larger depending on the tune.
- Small magnetic field errors cause the resonances.
  - Integer resonances
  - Half-integer resonances
  - Third order resonances
  - x-y coupling resonances



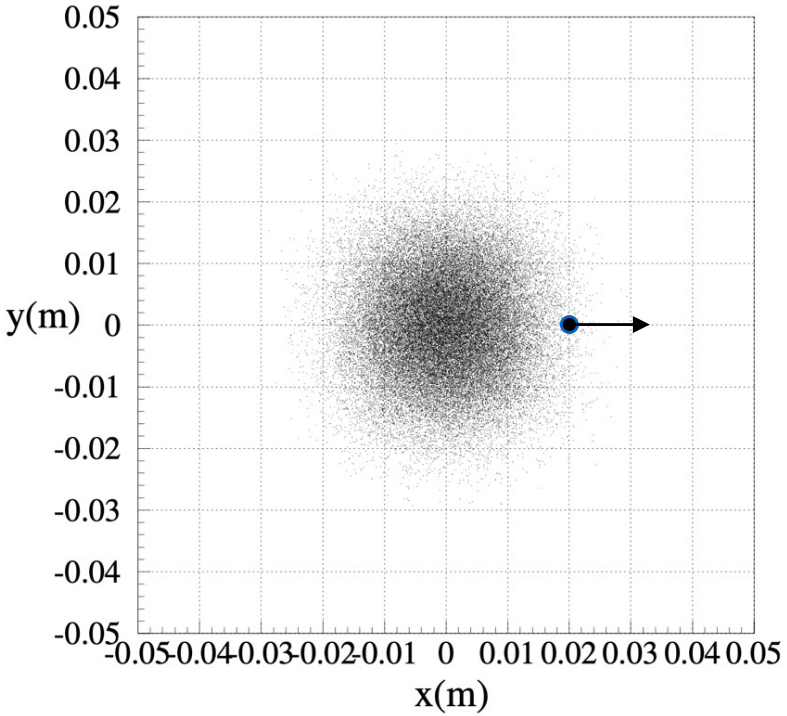
Position along MR

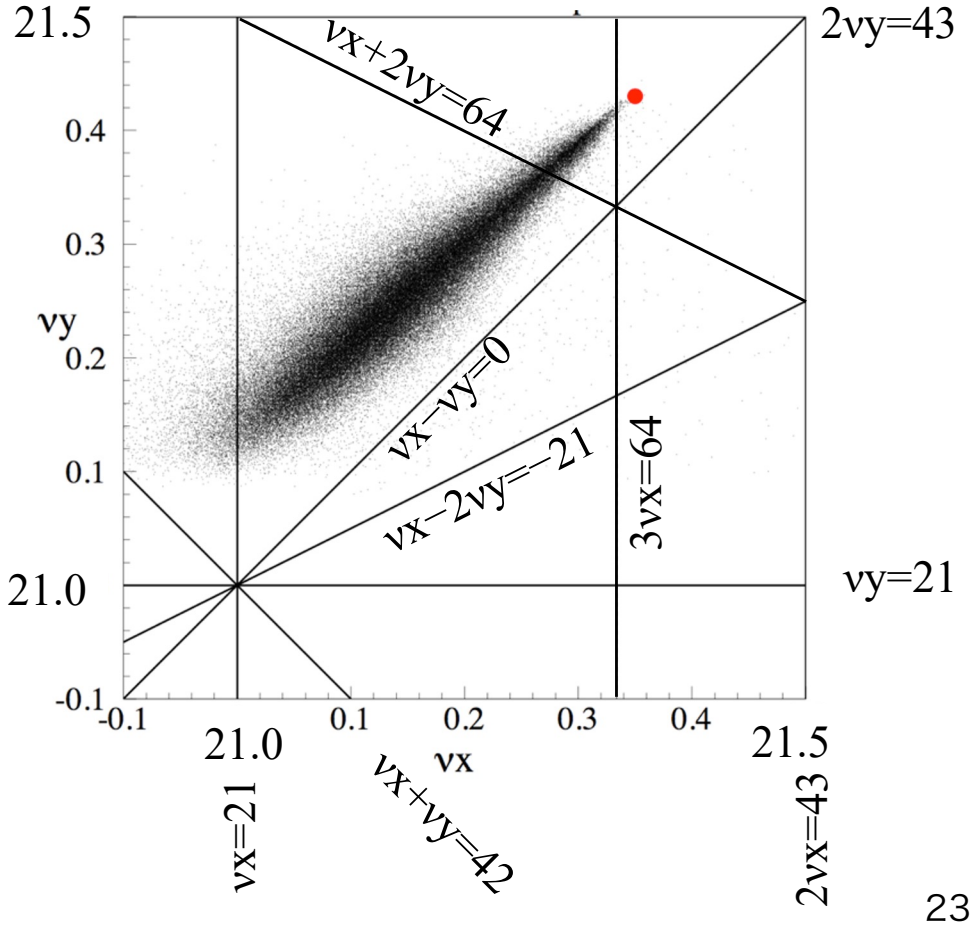


Space Charge Effect

- Space charge force, which is repulsive force between protons, diffuses the beam.

Proton distribution in the beam





Contents

- Introduction
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- Efforts for performance improvement
- Accelerators in KEK
- Summary

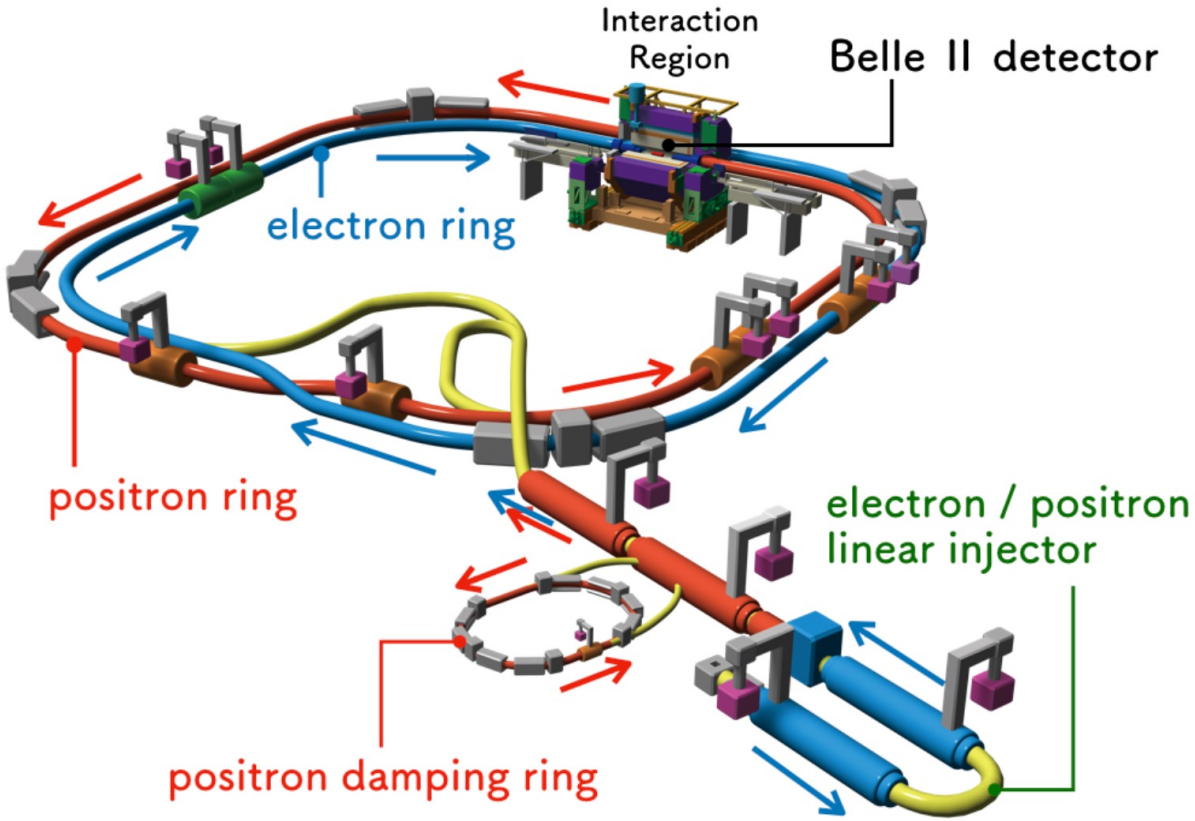
Accelerators in KEK

For Science Experiments

- SuperKEKB
  - ➢ e^-/e^+ Collider
    - Linear Injector (e^-/e^+)
    - Damping Ring (e^+)
    - Low Energy Ring (e^+)
    - High Energy Ring (e^-)
- Photon Factory (PF)/PF-AR
  - ➢ Photon : X-ray
    - Linear Injector (e^-)
    - Photon Factory Ring (e^-)
    - Accumulator Ring (e^-)
- J-PARC
  - ➢ proton/secondary particles
    - LINAC (H^-)
    - RCS (p)
    - MR (p)

For Accelerator Researches

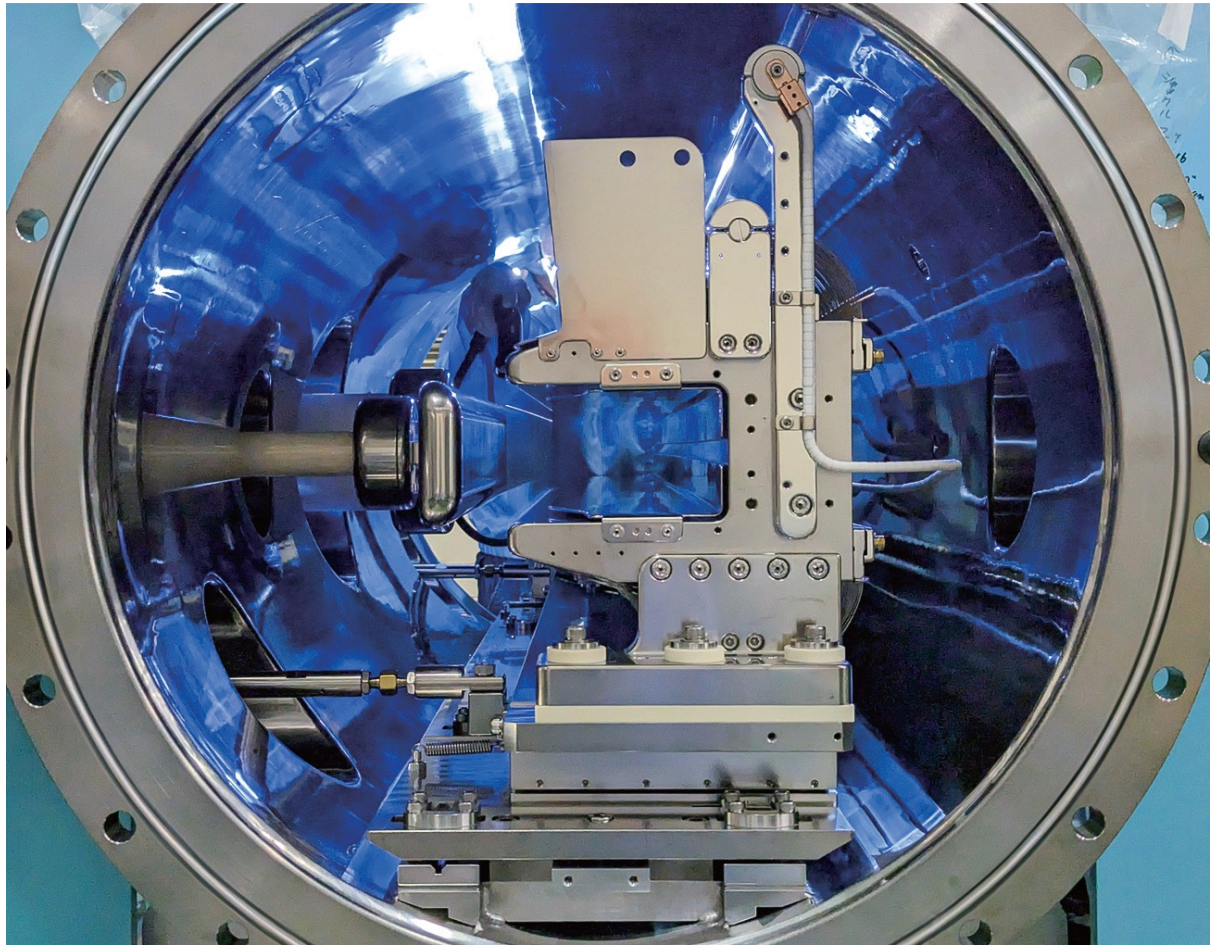
- cERL/ATF/STF



Schematic drawing of SuperKEKB/Belle II facility

Technologies for Accelerators

- Magnet
- RF cavity
- Super conductor/Cryogenic
- High Vacuum
- Surface treatment
- Alignment
- Radiation measurement
- Radiation protection
- Beam monitors
- Electronics
- Data acquisition
- Computing



Electro-static septum at J-PARC MR
Beam extraction device with electric field
100 kV applied at the electrode
500 Ribbons made with W/Re 30 μm thick
Remote alignment mechanism
Ultra high vacuum chamber $\leq 1\times10^{-6}$ Pa
(Pressure at the International Space Station)

Summary

- Accelerators have been operated for various experiments, such as
  - elementary particle physics,
  - nuclear physics,
  - material and life sciences, and
  - accelerator researches.
- We keep improving accelerator performances for the demands of experiments.
- Accelerators requires various kinds of researches and technologies.
- Summer student program should provide valuable experiences through the researches.